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A Literature Review of the Effects of Waves on Aquatic Plants

35



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A Literature Review of the Effects of Waves on Aquatic Plants

by

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Preface

The Long Term Resource Monitoring Program (LTRMP) was authorized under the Water Resources Development Act of 1986 (Public Law 99-662) as an element of the U.S. Army Corps of Engineers' Environmental Management Program. The LTRMP is being implemented by the Environmental Management Technical Center, an office of the National Biological Survey, in cooperation with the five Upper Mississippi River System states, Illinois, Iowa, Minnesota, Missouri, and Wisconsin, with guidance and Program responsibility provided by the U.S. Army Corps of Engineers.

The mission of the LTRMP is to provide decision makers with information to maintain the Upper Mississippi River System as a viable large river ecosystem given its multiple-use character. The long-term goals of the Program are to understand the system, determine resource trends and impacts, develop management alternatives, manage information, and develop useful products.

This review is part of a Corps of Engineers study on the effects of navigation on the Upper Mississippi River System. The purpose of the review is to describe the physical impacts on vegetation from waves generated by commercial and recreational traffic and by natural forces, and the ecological consequences of these impacts. This report satisfies Work Unit A, *Effects of Vessel Passage on Wave Regime and Sediment Dynamics* and Work Unit B, *Evaluation of Impacts of Navigation-Induced Waves on Aquatic Macrophytes*, in Strategy 1.2.2, *Determine Effects of Navigation on Selected Components and Processes of the Upper Mississippi River System Ecosystem*, under Objective 1.2, *Implement Ecological Research*, under Goal 1, *Develop a Better Understanding of the Ecology of the Upper Mississippi River System and its Resource Problems*, as specified in the Operating Plan for the Long Term Resource Monitoring Program (USFWS 1992).

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Introduction

The aquatic plant communities of the Upper Mississippi River have the capacity to stabilize sediments, improve water quality, and provide habitat and food for invertebrates, fish, waterfowl, and mammals (Martin et al. 1951; Sculthorpe 1967; Sparks 1984).

The impacts of wave energy caused by wind and by recreational and commercial traffic in the Upper Mississippi River on aquatic plant community stability, productivity, and diversity are unknown, although the physical effects of barge traffic on wave generation, sediment suspension, and transport into side channels have been examined. Several reports have stated the need for experimental studies addressing the effects of navigation on aquatic plants in the Upper Mississippi River System (Lubinski et al. 1980, 1981; Rasmussen 1983; Leake and Keevin 1990; Vohs et al. 1993), and study plans have been developed but not yet carried out (U.S. Army Corps of Engineers 1989, 1993).

This review is part of a Corps of Engineers study on the effects of navigation on the Upper Mississippi River. The purpose of the review is to describe the physical impacts on vegetation from waves generated by commercial and recreational traffic and by natural forces, and the ecological consequences of these impacts.

Characteristics of Waves

Waves Produced by Natural Forces

Waves produced in deep water by either wind or gravity flow tend to have circular wave forms, which become elliptical as waves move toward shallow water (Håkanson 1977; Spence 1982). For wind-generated waves, Spence (1982) concluded that if the water depth is less than half of the wave length (referred to as the wave-mixed depth), wave energy can be transmitted to the bottom, where it may be sufficient to uproot plants directly as well as resuspending and transporting sediments, as shown by Carper and Bachmann (1984). Wave lengths of wind-generated waves depend upon effective fetch distance, wind velocity, and wind duration (Håkanson 1977; Keddy 1982).

Waves Produced by Commercial and Recreational Traffic

Commercial Traffic

Wave lengths of navigation-generated waves will depend on the vessel's velocity, distance from shore, size, shape and loading, upstream versus downstream traffic, and the frequency of vessel passage (Karaki and Van Hoften 1974; Berger and Associates 1980; Bhowmik et al. 1981a, 1981b, 1982, 1989; Maynard and Siemsen 1991; Mazumder et al. 1991).

As a barge-tow moves through the water, it creates diverging surge waves in front of the bow which radiate outward to the channel shores. Due to the friction between the vessel and moving water, return currents are created which accelerate in the opposite direction of vessel movement (Karaki and Van Hoften 1974). This velocity gradient is superimposed on the natural flow regime of the channel, such that a downstream vessel will cause a decrease in ambient water velocity at its mid-section (Bhowmik and Mazumder 1990), and a brief current reversal may occur (Schloesser and Manny 1989; Miller et al. 1990). As the return current develops and as water is drawn toward the

propeller, the water level around the vessel drops temporarily (drawdown). Drawdown is affected by channel cross-sectional area and will be greater in narrow channels (Hochstein and Adams 1989). Measurements by Bhowmik and Mazumder (1990) and Bhowmik et al. (1981) indicate the majority of drawdowns on the Illinois and Mississippi Rivers are approximately 0.1 m and last on the order of several minutes.

In the zone behind a barge-tow, wave structure and energy are influenced by the velocity and turbulence of flow. The stern waves are affected by the return current, by the propeller jet, tow speed, and channel cross-section (Fig. 1). Closer to shore, bow and stern waves interact to form a complex turbulent pattern. Velocity changes in the channel border area can be from 3 to 10 times ambient river velocity, and the duration of velocity increases can last as long as 15 min near shore (Mazumder et al. 1991). These velocity increases can be measured in side channels (Bhowmik et al. 1981c). Empirical equations have been developed relating generated wave height to vessel width, draft, velocity, and channel cross-sectional area (Bhowmik et al. 1981a, 1981b). In addition to shoreline effects, the propeller jet, wake flows, and displacement flows beneath barge-tows significantly increase near-bed velocities over ambient river velocities (Maynard and Siemsen 1991).

In shallow channels (defined by Sørensen as having depth less than approximately 1/20 the wave length), the wave patterns generated by vessel movement are a function of water depth (Sørensen 1973). The wave direction is solely dependent on vessel speed and water depth. Sørensen found that waves generated by model ship hulls touch channel bottom at Froude numbers $(V_p/(gd)^{1/2})$ where V_p = vessel speed; g = acceleration of gravity; d = water depth > 0.6 . For the Upper Mississippi River System, Bhowmik and Mazumder (1990) estimated that Froude numbers > 0.4 indicated that wave energy was being transmitted to bottom sediments.

Recreational Traffic

Recreational boat traffic can generate wave heights sufficient to increase sediment resuspension and damage vegetation. Bhowmik et al. (1990, 1991; Bhowmik and Soong 1992a, 1992b) found that cabin cruisers and towboats without barge convoys generated the largest wave trains on the Upper Mississippi River, with recreational traffic generating waves from 0.4 to 0.5 m high.

Physical Effects of Waves

Sediment Suspension by Natural Forces

Wind-generated resuspension of sediments within the wave-mixed depth has been documented for lakes (Carper and Bachmann 1984), lagoons, rivers, and estuaries (Schoellhamer and Levesque 1991). Suspended sediments decrease light availability to submersed vegetation (Otto and Enger 1960; Wetzel 1983), may abrade leaves (Sculthorpe 1967), and increase nutrient concentrations in the water column. In a shallow lake in Denmark, fluctuations in total phosphorus concentration in the water column had the same patterns and magnitude as resuspension events (Kristensen et al. 1992). Significantly higher chlorophyll and ammonium concentrations were found during wind resuspension in a tropical lagoon (Arfi et al. 1993), and resuspension was a major factor controlling overall productivity. In the Potomac River, Simon (1989) concluded from studies

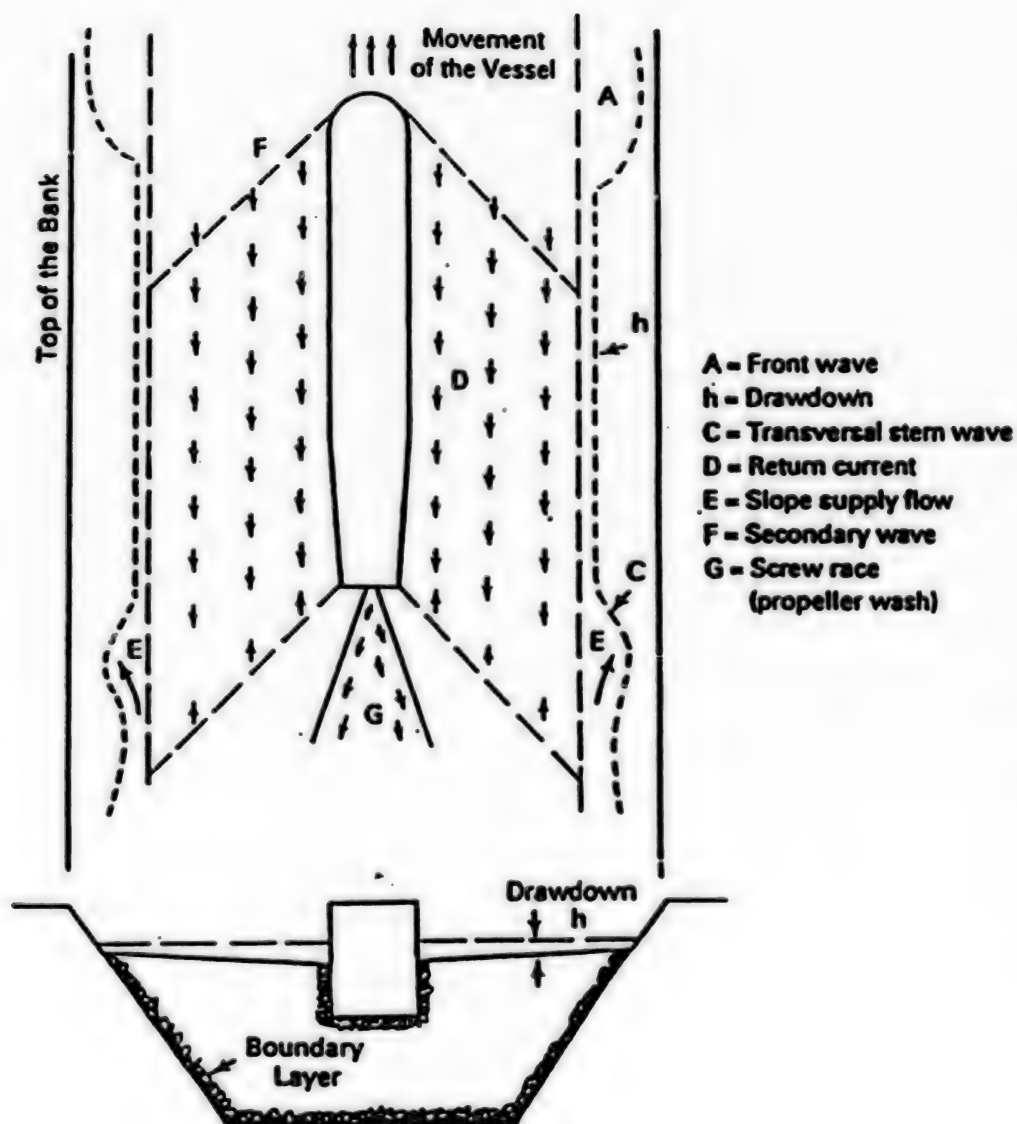


Figure 1. Schematic diagram showing the water motion generated by a ship (from Blaauw et al. 1984)

of wind-generated resuspension that "one resuspension event lasting minutes could mix more ammonium into the water column from desorption of ammonium from sediment solids than could be delivered . . . by passive flux from shallow-water sediments in 10-1,000 days." As nutrient concentrations in the water column increase, algal biomass increases, as reflected in higher chlorophyll concentrations (Arfi et al. 1993). Higher algal biomass, either plankton in the water or periphyton on leaf surfaces, will decrease light availability for submersed macrophytes and may precipitate their decline, as suggested, for example, by Phillips et al. (1978). Shading from epiphyte loading on *Ranunculus* leaves during low flows appeared to restrict macrophyte growth in the River Lambourn (Ham et al. 1981).

Sediment Resuspension by Vessels

In a study of sediment resuspension in the Ohio River, Berger and Associates, Inc. (1980) noted significant resuspension related to tow passage, which was related to tow size, with small tows having approximately half the impact of large tows. Significant increases in sediment suspension were noted for anchoring or maneuvering barges. Using rented barges and tows on the Ohio River, Bhowmik et al. (1989) observed sediment resuspension lasting from 25 to 30 min. Bhowmik et al. (1981a) described the effects of barge traffic on sediment resuspension in the Illinois and Mississippi Rivers. The increase in resuspension and transport into side channels was greatest when water flow was lowest, which was also the period when backwater deposition rates and sediment trapping efficiencies were highest. They noted that frequency of tow passage affected the duration of resuspension: " . . . successive tow passages at time intervals of less than 90 minutes result in extended periods of increased sediment concentration" Effects of tow passage were greater on the Illinois River than on the Upper Mississippi River due to the narrower channel of the Illinois (Bhowmik et al. 1981a; Adams 1992). In a similar study, Eckblad (1981) observed increases in turbidity in side channels during tow passage in Pool 9 of the Upper Mississippi River. At about half the sites, there was a brief decrease in ambient turbidity after a barge passage, followed by an increase above ambient levels. Eckblad postulated that the temporary decrease in turbidity was due to water being pulled out of side channels during drawdown. The largest increases in turbidity "were found at shallow side channels where wave wash appeared to be responsible for the resuspension of near shore sediments." In another study of Pool 9, Smart et al. (1985) found that the duration of increased suspended sediment associated with commercial navigation lasted approximately 90 min. On the Illinois River, Sparks et al. (1980) found statistically significant increases in suspended sediment in side channels with increasing tow traffic.

The direction of traffic affects the magnitude of resuspension, as observed by Claflin et al. (1981), with upbound traffic causing greater resuspension than downbound traffic. Similarly, Hochstein and Adams (1989) noted that the kinetic energy added to the channel for an upbound vessel is greater than that of a downbound vessel, since the directions of propeller wash, return flow, and ambient river flow are the same.

In addition to sediment resuspension, barge-tows may increase the mixing of effluent plumes from wastewater treatment plants, as shown by Stefan and Riley (1985). This effect is especially pronounced during summer low flows and may cause surges of effluent plumes.

In baseline studies of Pool 9, Eckblad (1981) noted that small recreational boats traveling at high speed in side channels increased suspended sediment concentrations.

Mixing

Due to low diffusion coefficients for gases in water, boundary layers depleted in carbon dioxide or rich in oxygen develop on submersed leaves of aquatic vegetation. These layers can be several times the leaf thickness (Wetzel 1988). In submersed plant beds, depending on density and type of vegetation, flow velocities can be reduced by 58% to 92% of velocity outside the bed (Madsen and Warncke 1983) to the order of millimeters per second (mm/s), (Marshall and Westlake 1989), resulting in laminar flow regimes and boundary layers up to nine times leaf thicknesses (Losee and Wetzel 1993). Carbon dioxide acquisition can be a limiting step for aquatic plant photosynthesis (Jenkins and Proctor 1985; Bowes and Salvucci 1989) and in plant distribution (Hough and Fornwell 1988); and high oxygen concentrations can inhibit carbon fixation by increasing the probability of photorespiration. Thus, moderate increases in flow or wave action can enhance mixing and dispersion of oxygen, and increase plant photosynthesis (Fonseca and Kenworthy 1987). In studies of *Ranunculus* and other macrophytes in the River Lambourn, Ham et al. (1982) found that *Ranunculus* beds expanded during periods of high spring discharges. Decreases in current velocity and silt deposition were correlated with decreases in *Ranunculus* growth (Ladle and Casey 1971). In the Chesapeake Bay, Carter et al. (1991) found that wind decreased dissolved oxygen in plant beds and also decreased thermal stratification, although this effect decreased in dense plant canopies. In Amazon floodplain lakes, basins with greater fetch (greater wind-generated wave energies) had greater vertical mixing and less anoxia (Melack 1984). In an early study of the Chesapeake Bay estuaries, Bourne (1932) found that high winds increased the amount of salt water entering embayments. At low water velocities, Westlake (1967, 1975) found that photosynthesis rates increased as velocity increased, but the rate of increase diminished with higher velocities. In a study of macrophyte growth in three sediment types in flowing waters, lower biomass was produced in coarser sediments and at high current velocities (Chambers et al. 1991). Thus, it appears that moderate increases in velocity enhance photosynthesis by boundary layer removal. However, when carbon dioxide is supplied at saturating levels to plants, higher velocities result in decreased net photosynthesis. This effect is possibly due to leaching of organic substances from leaf surfaces or to physical damage (Madsen et al. 1993). Thus, moderate wave action and current flow enhance plant productivity, but the appropriate definition of moderate velocities and wave energies which enhance growth may vary seasonally, with bed size, plant density, and species morphology.

Sediment Deposition

Deposition of fine sediments may stimulate plant growth by providing nutrients or, conversely, may decrease plant growth by shading if sediments are deposited on leaves (Ladle and Casey 1971) or may bury propagules so deeply they fail to germinate. In a study of English rivers that were channelized, Brookes (1988) compared species diversity in upstream control regions with diversity in the downstream channelized sections. Channelization increased suspended sediment concentrations and sediment deposition. In the channelized regions, submersed species diversity decreased due to burial. However, species response depended upon the ability of plants to alter their rooting depth. *Nasturtium*, a species which could alter its rooting depth, survived, whereas *Ranunculus*, which did not alter rooting depth, became buried. Ham et al. (1981) found that the growth of *Ranunculus* beds was restricted following sediment deposition resulting from dredging in the Lambourn River. In a study of *Vallisneria spiralis* tuber germination, Rybicki and Carter (1986) found that burial of tubers by 200 mm of sediment decreased germination rates and subsequent growth. In a study of *Sagittaria latifolia* and *S. rigida* beds in open areas and backwaters of Pool 9 of the Upper Mississippi River, Clark and Clay (1985) observed that beds had greater standing crop in open areas despite their greater exposure. They concluded that the

observed siltation in backwaters resulted in less productive *Sagittaria* beds. Fine sediments deposited during seasonal low flows may create a substrate for plant expansion, only to be resuspended and plants uprooted when flows increase, as observed by Sirjola (1969), Edwards (1969), Hynes (1970), and Haslam (1978).

Extremes: Storms, Winter Navigation, Navigation in Low Flow

Storms

Superimposed upon wind- and/or navigation-induced shear and sediment resuspension, storms and spates can destroy or restructure aquatic plant communities and may be responsible for the cyclical growth of vegetation (Haslam 1987). The frequency and intensity of storms may determine the interval in which plant communities develop, so that after frequent or very severe storms vegetation may recover very slowly (Haslam 1978; Carter et al. 1985). Major declines in reed populations have been noted after severe storms (Ostendorf 1989; Stark and Dienst 1989). Storm damage at the end of a growing season may remove propagules and result in decreased plant populations in the following year (Haslam 1978). Floods may change species composition and decrease seed production by aquatic vegetation (Birch et al. 1988). Hurricanes result in heavy runoff which scours channels, uproots vegetation, and redeposits sediments. In Chesapeake Bay, the effects of hurricanes can be seen in the deposition of sedimentary layers (Bayley et al. 1978). The loss of submersed vegetation in the tidal Potomac River and Estuary was likely due to uprooting and/or siltation caused by extensive storm damage in the 1930s, during which sediment was deposited to a depth of over 200 mm (Carter et al. 1985). Stream vegetation which reproduces mainly by clonal propagation may be removed from swifter flowing sites during storm events (Butcher 1933; Bilby 1977) to recolonize slower sites. Poor agricultural practices in the watershed may exacerbate flooding effects and sediment deposition during storms (Edwards 1969). Where beds of vegetation remain after storms, their structure may be damaged. Storm-damaged seagrass beds showed no difference in sediment-trapping ability when compared with unvegetated areas (Ward et al. 1984).

Navigation in Ice and in Low Flows

Barge traffic at the end or beginning of the navigation season may also increase sediment resuspension and deposition as vessel power is increased for navigation in ice (Hochstein and Adams 1989). The decrease in numbers and biomass of macrophyte taxa in shipping channels was attributed to pressure waves created by winter navigation in the St. Lawrence River (Raynal and Geis 1978, in Schloesser and Manny 1989). Pressure waves created by navigation in ice increase macrophyte drift (Poe and Edsall 1982).

As barge-tows encounter navigational difficulties, they may deviate from the sailing line into shallow areas and areas closer to shore, increasing sediment resuspension and shore erosion (Simons et al. 1981, 1988). Similarly, navigation during low flows can also increase sediment resuspension and transport of sediment into side channels (Simons et al. 1981, 1988).

Comparison of Wind and Navigation Effects

Drawdown

Navigation causes predictable drawdown, resulting in exposure of shoreline vegetation for short periods. During drawdown, floating vegetation has been observed to be moved from channel borders into the main channel (W. R. Clark, Iowa State University, personal communication). High winds can also cause drawdown; however, the extent to which this occurs is less predictable and may be significant only for portions of the river unprotected by bluffs and where fetch distances are long.

Direction, Magnitude of Energy Input

The relative contributions of wind and navigation energies to uprooting and sediment transport are difficult to assess. Navigation effects may be easier to predict than stochastic wind and storm energy inputs. Navigation energy inputs into shorelines can be predicted based on the vessel parameters described above. Wind energy inputs will depend on shoreline geometry in relation to the prevailing wind direction, speed, and effective fetch. Bhowmik (1976) developed shore protection criteria for Illinois lakes and ponds based on measured wind-generated wave heights and noted that wave heights produced by recreational boat traffic and wind were in some cases similar. The magnitude of energy inputs from navigation and wind will also be affected by flow conditions in rivers and backwaters, so that both inputs will have greater effects during low flows. Stefan and Anderson (1980) modeled flow and exchange in an Upper Mississippi River impoundment. Under low flow conditions, wind shear stress was a major driving force governing sediment exchange between backwaters and the main channel. Although in general navigation tows have the effect of moving suspended sediments into backwaters, Sparks et al. (1980) observed that wind-generated waves could occasionally push turbid water from a backwater into the main channel of the Illinois River.

Periodicity, Frequency, and Duration

Wind and barge energy inputs were compared on the Illinois and Upper Mississippi Rivers (Bhowmik et al. 1982). While waves were generated more frequently by river traffic, these waves generally lasted for minutes in comparison with wind-generated waves, which could last for hours at high wind velocities. However, navigation events occurred several times per day, resulting in durations of 30 to 75 min, while significant wind-generated waves were likely to occur only a few times per year. Navigation-generated wave heights were generally <0.3 m, whereas wave heights for a 2-year, 6-hour duration wind ranged from 0.3 (Illinois River) to 0.4 m (Mississippi River).

Effects of Waves on Aquatic Macrophytes

Morphology, Resistance, and Uprooting

The increase in wave energy transmitted to the bottom may be the main factor limiting the minimum or "upslope" depth of aquatic vegetation, either through direct uprooting or through the secondary effect of sediment sorting and removal of finer, more organic sediments (Jupp and Spence 1977; Spence 1982; Ward et al. 1984; Keddy 1985). For example, in a study of wild rice (*Zizania aquatica*), Lee and Stewart (1971) observed that greatest mortality occurred during the period when leaves were still submerged and plants were physically uprooted by wave action. Chambers (1987) provided the first quantitative evidence that the minimum depth of colonization (the upslope limit) for several species of submersed macrophytes was a function of the wave mixed depth.

The resistance of plants to uprooting varies with the growth form, water depth (plants in shallower water receive more force than plants in deeper water), the extent of beds, and the density of vegetation. Studies of plant resistance to uprooting have ranged from observations of species survival and zonation patterns as a function of wave energy (Heslop-Harrison 1955; Haslam 1971, 1978; Sculthorpe 1967) to experimental comparative analyses of the mechanical properties of leaves, stems (or kelp stipes), and root morphology to analysis of the roughness characteristics of aquatic vegetation in canals and streams (Pitlo and Dawson 1990) to modeling wave attenuation by vegetation (Kobayashi et al. 1993).

The most comprehensive mechanical analyses of aquatic plants to date have been done with marine algae and seagrasses to understand how the properties and shapes of these organisms contribute to species zonation patterns in rocky intertidal zones (Carstens 1968; Koehl 1982; Koehl 1984; Vogel 1984; Denny 1988). In these studies, the drag, lift, and tensile strengths of organisms have been measured and compared with the resistance of plants to breakage or uprooting. It appears that plants avoid destruction either by producing long, thin, flexible leaves and stems, which collapse in high flows to reduce form drag, or by being shorter, less extensible but with greater cross-sectional area to increase strength and resistance to breaking.

Similar analyses of hydraulic resistance and tensile strength have been done for freshwater macrophytes growing in rivers by Haslam (1978) and Dawson and Robinson (1985). Haslam has classified river plants on the basis of their relative hydraulic resistances (measured with a spring balance) as high (emergent or submergent, bushy or branched plants), medium (semi-streamlined or streamlined emergents or submergents; e.g., *Potamogeton pectinatus* when much branched), or low (streamlined submergents; e.g., *Sparganium emersum*); however, the hydraulic resistance can vary within a species from highly streamlined to highly branched. Similarly, Haslam has ranked plants on the basis of relative anchoring strength, but as with hydraulic resistance, the same species of plant may belong to more than one category of strength based on its growth form. In general, plants with deeper roots and strap leaves will resist uprooting better than those with coarse or large leaves with high hydraulic resistance and shallow rooting systems. The cordate, sagittate, or triangular leaves of floating leaved plants and emergents may reduce drag and resist uprooting (Hutchinson 1975) during windstorms. Heslop-Harrison (1955) noted that *Nuphar lutea* could exist in more exposed reaches of the littoral zone than could *Nymphaea*, on the basis of its stronger leaf. Due to leaf and stem morphology, culms of *Phragmites* may experience greater erosive force than the narrow spiraling leaves of *Typha* or species with short, stiff rosettes and deep root systems (Sculthorpe 1967; Hutchinson 1975). Factor analysis and ordinations for species distributions along physical gradients in Lake George, New York, indicated that the presence of species with stiff

foliage and extensive roots (*Eriocaulon* sp.) was strongly correlated with measures of exposure based on fetch (Collins et al. 1987). Recently, Brewer and Parker (1990) examined extensibility, cross-sectional area, and tensile strength of freshwater macrophyte species (*Myriophyllum spicatum*, *Ranunculus aquatilis*, *Elodea canadensis*, *Potamogeton alpinus*, *P. richardsonii*, and *P. filiformis/pectinatus*). Although age differences between species may have contributed to mechanical properties, the study showed significant interspecific differences in extensibility and tensile strength, with *P. filiformis/pectinatus* (found in shallow water in this study) having greatest tensile strength and *Myriophyllum spicatum* (deep water species) having greatest extensibility.

In flow regimes that are not damaging enough to cause uprooting, aquatic plant beds dissipate energy based on their roughness and develop bed densities as a function of current velocity. Fonseca et al. (1983) described a model for seagrass bed development (Fig. 2) in which seagrasses develop to a bed size and density where they are in equilibrium with "the reduction of current flow provided by their canopy, sediment stabilization afforded by their root-rhizome complex, and the increase in velocity caused by any mounding associated with their own presence."

As beds reduce velocity, the differences between flow outside and inside beds increase (Adams et al. 1986), creating flow acceleration around a canopy and possibly increasing local erosion (Gambi et al. 1990). The time for wave travel through a bed will increase (Hamill 1983) and local sediment deposition will occur (Haslam 1978).

Flow retardation due to vegetation or other factors is quantified by Manning's "n," a roughness coefficient incorporated into the equation describing flow through a channel:

$$Q = (1/n)(A \cdot R^{2/3} S^{1/2}),$$

where Q = flow rate, A = cross-sectional channel area, R = hydraulic radius (the cross-sectional area divided by the wetted perimeter), and S = channel slope.

Manning's n has been calculated for a variety of freshwater and marine plants, particularly weeds which retard flow in streams, navigation, or irrigation waterways (reviewed by Dawson and Charlton 1988; Pitlo and Dawson 1990). Roughness coefficients vary with species morphology (Fonseca and Fisher 1986), are inversely related to flow, and increase proportionately with plant biomass increase (Brooker et al. 1978; Dawson 1978a). The rate of sediment deposition increases with roughness increases (Dawson 1978a). Aquatic plant roughness may decrease with increasing flow velocity as the plant stems bend in the direction of flow (Dawson and Robinson 1985; Fonseca et al. 1982). Roughness also decreases as flow depth increases (Petryk and Bosmajian 1975; Pitlo 1982). Thus, plant resistance to flow, as expressed by roughness coefficients, may vary widely throughout a growing season.

Fragmentation, Windrowing, and Dispersal

Uprooted plants or broken plant parts may serve as propagules for dispersal. Brewer and Parker (1990) noted that weaker-stemmed elodeid-type plants (*Elodea*, *Myriophyllum*) broke during late summer drawdowns, to form floating mats. Similarly, Sculthorpe (1967) described floating "sudd" communities in tropical rivers, drifting islands of aquatic vegetation uprooted by winds and currents, which can reestablish downstream. Fragmentation will be strongly affected by seasonal changes in weather patterns and storm frequency in addition to seasonal changes in navigation (described below). Waves may also act to transport and windrow floating species such as lemnae (Weller 1981) or floating seeds (Cook 1987) and clonal fragments along with litter (wood debris)

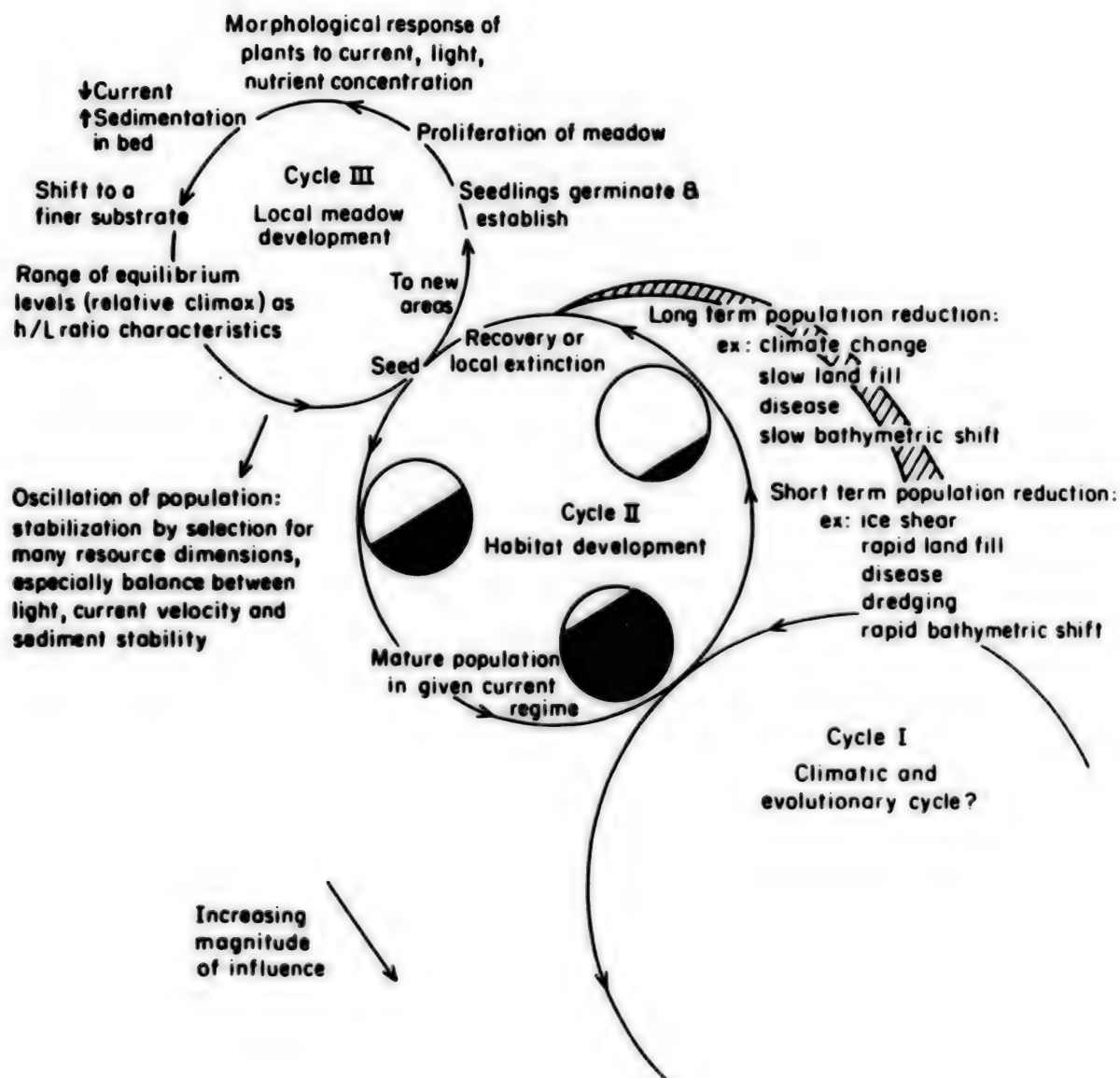


Figure 2. Development of seagrass meadows as influenced by physical factors (from Fonseca et al. 1983). Reprinted by permission.

along exposed lake and river banks (Nilsson and Grelsson 1990). These processes have been shown to be significant in the regeneration of bald cypress communities (Schneider and Sharitz 1988) and in the dispersal of *Elodea* fragments in Norway (Rørslett 1969).

Exposure and Drawdown

As plants are uprooted from shorelines due to wind- or navigation-generated wave action, bank erosion and sediment sorting can result in steeper shoreline slopes containing coarser, less organic sediments, which are in turn more susceptible to future erosion. Steeper slopes may be less effective in modulating wave action in the littoral zone. Similar effects may be created by the drawdown and slope exposure which occur during barge movement in restricted channels (Karaki and Van Hoften 1974). Exposure and the resulting changes in slope characteristics may determine species composition and productivity of aquatic plant communities on lakeshores (Duarte and Kalff 1986) or on river margins (Roberts and Ludwig 1991).

Plants may be absent in extreme exposures, as described for Lake Ontario shorelines (Crowder and Painter 1991). In general, species richness is greatest at intermediate levels of exposure disturbance (Keddy 1983, 1984). The life history characteristics of plants occurring along disturbance and fertility gradients along river margins were summarized in a model proposed by Day et al. (1988), based on multivariate analysis of vegetation occurring in riverine wetlands of the Ottawa River. Five types of strategies were proposed: "Clonal dominants" (*Typha latifolia*, *Sparganium eurycarpum*) formed extensive rhizomes and occurred in fertile, undisturbed areas; these areas had low species richness, but had the highest net primary productivity. "Gap colonizers" lacked rhizomes, produced many seeds, and germinated on small clearings, such as those caused by ice scour or sudden bank slumping. Gap colonizers included weed species such as purple loosestrife (*Lythrum salicaria*). "Stress tolerators" (*Eleocharis smallii*, *Ranunculus flammula*, *Eriocaulon septangulare*, *Myriophyllum tenellum*, *Juncus pelocarpus*, *Isoetes* spp.) were small evergreen species that occurred on exposed, fertile sites where wave action removed litter. These sites had the greatest species diversity. "Reeds" with deeply buried rhizomes (*Equisetum fluviatile*, *Eleocharis smallii*, *Scirpus acutus*, and *S. americanus*) occurred on infertile shorelines where litter was removed by flowing water, the shoreline was scoured, and upper layers of sediment were churned. "Ruderals" reproduced annually from seeds and were found only in areas of both high fertility and high disturbance, on mudflats.

In a comparison of plant productivity at an exposed site with plant productivity on similar sediments in enclosures sheltered from wave activity, Jupp and Spence (1977) found that 80% of biomass decrease at the exposed site was due to wave action. The development of *Phragmites* beds has been negatively correlated with wave exposure and the concomitant removal of litter (Ondok 1970). In a study of lakes in Vilas County, Wisconsin, Wilson (1935) described *Typha* colonies being prevented from lakeward expansion by the mechanical action of waves. In experiments designed to determine whether direct wave action or indirect sediment effects were more important in determining plant biomass, Coops et al. (1991) found that plant biomass of *Phragmites* and two species of *Scirpus* was more affected by direct wave action than by secondary sediment nutrient effects. However, *Typha* production was affected by both nutrients and site exposure.

In exposed sites, plant recovery after a disturbance may be slower than at more sheltered sites, as sediment nutrients are removed with resuspension of finer sediments (Keddy 1985). In general, greater wave exposure will decrease species diversity in nutrient-poor sediments (Grelsson and Nilsson 1991). In contrast, species richness, productivity, and expansion at a eutrophic site

have been shown to be greater at an exposed site than in a sheltered site (Weisner 1987, 1991). The mechanism in this case appears to be that fine, flocculant shifting sediments provided less stable anchoring, had higher oxygen demand, and reduced light availability at the sheltered site. Thus, plants may be limited at sites by very coarse sediments or by fine, flocculant sediments (Barko and Smart 1986).

Wave action may remove seeds and overwintering buds from seed and bud banks (Foote and Kadlec 1988), and in general the seed banks of shores with high exposure appear to be less diverse than the seed banks of sheltered sites (Grelsson and Nilsson 1991; Wisheu and Keddy 1991).

Studies of the Effects of Traffic on Aquatic Vegetation

Commercial Traffic

The loss of aquatic plants in English navigation canals has been described by Haslam (1987). Describing the Illinois River, Sparks (1975) noted that, in areas sheltered from the wind, bank erosion occurred due to boat wave action. This resulted in the loss of trees from eroding levees. He also described the loss of rooted aquatic plants in Lake Chautauqua related to increased turbidity from suspended sediments. The loss of *Phragmites* beds in Pool 5 has been related to altered flow patterns and sand deposition (Fremling 1973; Olson and Meyer 1976). In main channel areas of the Upper Mississippi River, periphyton communities are less diverse, displaying two-dimensional architecture in comparison with the more diverse, three-dimensional flora in backwaters (Luttenton et al. 1986). Aquatic plant species were less diverse; shorter, narrow-leaved species were more common; and abundance was lower in shipping channels compared with non-shipping channels of the Detroit and St. Clair Rivers (Schloesser and Manny 1982, 1989). These differences were attributed to (1) disruption of normally unidirectional flow resulting in physical uprooting and (2) erosion of low-density substrates. The U.S. Fish and Wildlife Service (1987) related decreased areal extent of submersed aquatic plants with reductions in the photic zone caused by increased suspended sediment. Comparing sediment texture and light availability as factors affecting aquatic plant distribution in the Upper Mississippi River, Roseboom et al. (1992) concluded that presence of vegetation was more closely related to light availability than to sediment texture.

Sediment transport into backwaters results in loss of pool volume: Pool 19 has lost 55% of its capacity due to sedimentation (Bhowmik and Adams 1986; Bhowmik et al. 1986). It is estimated that, at present sedimentation rates from upland erosion and transport of fine sediments, most of the open water areas of backwater lakes will be marshlands within the next century (Chen and Simons 1986).

Recreational Traffic

Recreational boat props were the most important factor in the dispersal of aquatic weed fragments between New Zealand lakes (Johnstone et al. 1985). Liddle and Scorgie (1980) reviewed the effects of recreational boating on freshwater plants and found that recreational traffic increased turbulence, cutting by propellers, direct contact, and destruction (Fig. 3). Sukopp (1971) described prop wash and direct contact damaging *Phragmites* beds. Significant increases in turbidity as a function of recreational boat traffic were observed by Hilton and Phillips (1982). The increase in turbidity remained above ambient levels for up to 5.5 hours. The effects of recreational

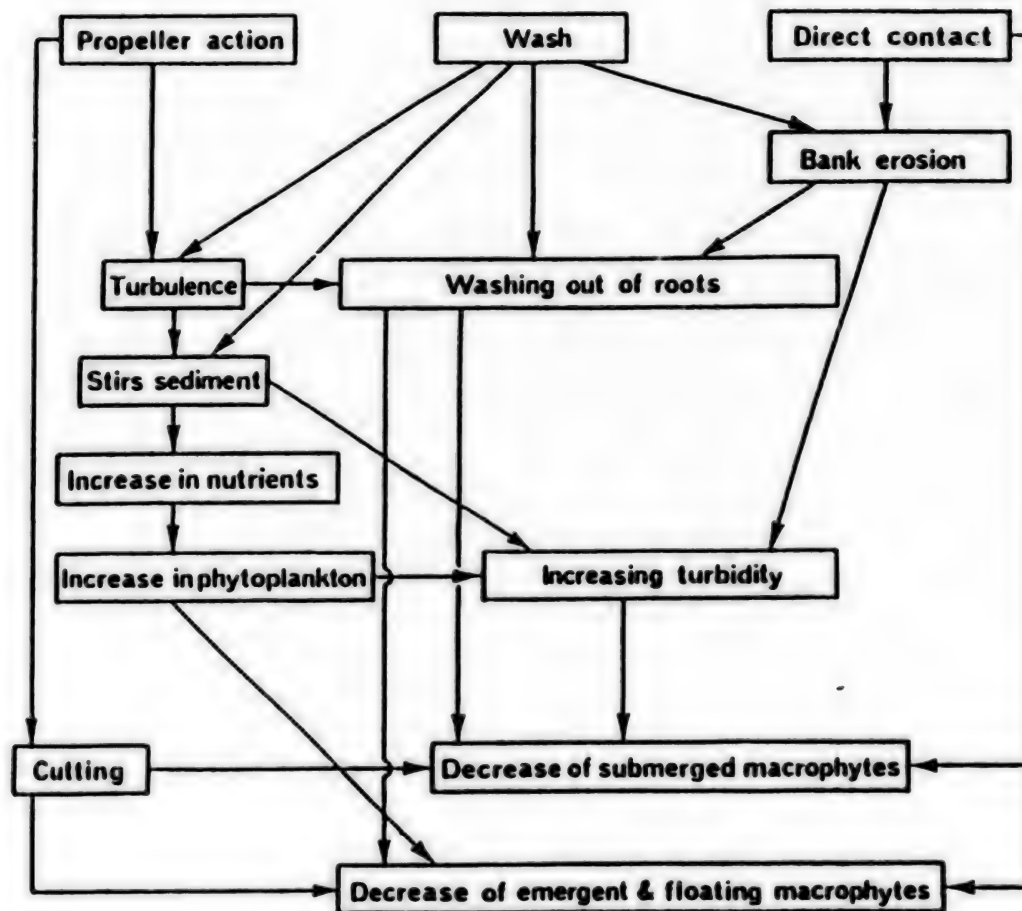


Figure 3. The impacts of recreational traffic on macrophytes (from Liddle and Scorgie 1980)

craft on submergent and emergent vegetation in English canals were studied by Murphy and Eaton (1983). Cluster analysis was used to classify sites on the basis of boat traffic, turbidity, macrophyte abundance, and species composition. Submergent vegetation was highly negatively correlated with critical boat traffic frequency. Emergent vegetation showed the same trend, with a lower correlation coefficient. The seasonal pattern of traffic in different canals affected the course of macrophyte community development. Direct destruction by propeller cutting was noted. Sediment resuspension was also observed and was shown to be largely inorganic, reflecting bottom sediment resuspension rather than phytoplankton stimulation. In the River Vecht (Netherlands), Vermaat and De Bruyne (1993) used transplant experiments with and without protective breakwaters and showed that growth of *Potamogeton pectinatus* was negatively affected by physical damage from recreational boat traffic.

Summary

Aquatic plants, due to their location in littoral, shoreline, or rocky intertidal zones, are affected by wave energy generated from tides, wind, and/or traffic. The interactions between waves and vegetation are summarized in Figures 2 and 3. Waves act directly by uprooting or fragmenting plants. Indirectly, wave action resuspends and transports sediments, resulting in coarser sediment textures in areas with high wave exposure, and sediment texture gradients from coarse sediments in high exposure areas to fine, higher nutrient sediments in sheltered sites. Suspended sediments affect plant growth by decreasing light availability, by scouring leaves, or (as a result of nutrient enrichment in the water column) by stimulating phytoplankton and periphyton blooms, which shade plants. Sediment deposition may enhance plant productivity by providing nutrients or may bury propagules and decrease germination and growth. The frequency, magnitude, and duration of wave energy inputs can be the principal factors determining species dispersal, diversity, and productivity at a particular site. Changes in the nature of wave disturbance may directly affect plant species composition and abundance, leading to changes in other components of an aquatic ecosystem. While affected by wave energy, aquatic plants also dissipate this energy, modifying their physical environment by decreasing water velocities, which in turn decrease mixing and increase sediment deposition (Hynes 1970). Thus, the presence of aquatic vegetation creates local zones of low water velocity which decrease erosion and increase water clarity and dissolved oxygen.

The effects of commercial and recreational traffic can be destructive to aquatic vegetation due to increases in wave energy, turbulent wave action impinging on shorelines (Kearney, Inc. 1980), increases in suspended sediment observed during barge-tow passage, and increased siltation observed in backwaters.

The potential for damage to aquatic vegetation from commercial and recreational traffic depends on vessel and channel characteristics. Navigation vessel characteristics which affect the wave height, wave velocity of bow and stern waves, and drawdown depend on size, blocking factor, tonnage, loaded/unloaded draft, velocity, direction of travel (upstream versus downstream), frequency of vessel passage, and distance from shore. Recreational traffic effects are also related to the frequency of passage, boat velocity, and hull characteristics. Channel characteristics which affect the degree of sediment resuspension include channel configuration (i.e., sinuosity), cross-section, bed roughness, sediment texture, sediment inputs from tributaries, connections between the main channel, side channels, and backwaters, and seasonal variation in river flow characteristics.

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For this review, we sought original research articles. The following computer databases were searched for appropriate key words: Water Resources abstracts, AGRICOLA, Applied Science and Technology Index, Biology and Agriculture Index, General Science Index, Government Document Abstracts, Wildlife and Fisheries Reviews, and the Upper Mississippi River Basin Commission databases. We wish to acknowledge the Corps of Engineers, Upper Mississippi River-Illinois Waterway System Navigation Study, for providing major support to this investigation and the cheerful assistance of Ms. Jean Schmidt at the St. Paul District of the Corps of Engineers, the Illinois State Water Survey, the Illinois Natural History Survey, the Aquatic Plant Center at the University of Florida at Gainesville, Terry D'Erchia of the National Biological Survey's Environmental Management Technical Center (EMTC), and staff of the Waterways Experiment Station, Vicksburg, Mississippi. We also wish to thank Sara Rogers, EMTC, and Dan Wilcox, Corps of Engineers, for their comments on an earlier draft of this manuscript.

References

- Adams, J. R. 1992. Sediment concentration changes caused by barge tows. Pages 677-682 in M. Jennings and N. G. Bhowmik, editors. *Proceedings of the American Society of Civil Engineers, Hydraulic Engineering Sessions at Water Forum '92, Baltimore, Maryland, August 2-6, 1992.*
- Adams, J. R., N. G. Bhowmik, S. D. Frank, and R.V. Anderson. 1986. Development of the Nauvoo Point plant bed. Pages 1984-1991 in *Water Forum '86: World Water Issues in Evolution.* Long Beach, California, August 4-6, 1986.
- Arfi, R., D. Guiral, and M. Bouvy. 1993. Wind-induced resuspension in a shallow tropical lagoon. *Estuarine, Coastal and Shelf Science* 36:587-604.
- Barko, J. W., and R. M. Smart. 1986. Sediment-related mechanisms of growth limitation in submersed macrophytes. *Ecology* 67(5):1328-1340.
- Bayley, S., V. D. Stotts, P. F. Springer, and J. Steenis. 1978. Changes in submerged aquatic macrophyte populations at the head of Chesapeake Bay, 1958-1975. *Estuaries* 1(3):73-84.
- Berger, L., and Associates, Inc. 1980. Environmental and physical impact studies for Gallipolis Locks and Dam, Ohio River: Analysis of the effect of tow traffic on the physical components of the environment. Report for Corps of Engineers, Huntington District, West Virginia.
- Bhowmik, N. G. 1976. Development of criteria for shore protection against wind-generated waves for lakes and ponds in Illinois. University of Illinois. Water Resources Center Research Report 107.
- Bhowmik, N. G., and J. R. Adams. 1986. The hydrologic environment of Pool 19 of the Upper Mississippi River. M. M. Smart, K. S. Lubinski, and R. A. Schnick, editors. *Ecology of the Upper Mississippi River.* Hydrobiologia 136:21-30.
- Bhowmik, N. G., J. R. Adams, A. P. Bonini, C. Guo, D. Kisser, and M. Sexton. 1981a. Resuspension and lateral movement of sediment by tow traffic on the Upper Mississippi River and Illinois River. Report for Environmental Work Team, Upper Mississippi River Basin Commission Master Plan, Minneapolis, Minnesota. Illinois State Water Survey, Champaign, Illinois. Contract Report 269. 112 pp.
- Bhowmik, N. G., J. R. Adams, and R. P. Sparks. 1986. Fate of navigation pool on Mississippi River. *American Society of Civil Engineers, Journal of Hydraulic Engineering* 112:967-970.
- Bhowmik, N. G., M. Demissie, and S. Osakada. 1981b. Waves and drawdown generated by river traffic on the Illinois and Mississippi Rivers. Illinois State Water Survey, Champaign, Illinois. Contract Report 271.
- Bhowmik, N. G., M. Demissie, and C. Y. Guo. 1982. Waves generated by river traffic and wind on the Illinois and Mississippi Rivers. Illinois State Water Survey, Champaign, Illinois. Contract Report 293.

- Bhowmik, N. G., M. T. Lee, W. C. Bogner, and W. Fitzpatrick. 1981c. The effects of Illinois River traffic on water and sediment input into a side channel. Illinois State Water Survey, Champaign, Illinois. Contract Report 270.
- Bhowmik, N. G., and B. S. Mazumder. 1990. Physical forces generated by barge-tow traffic within a navigable waterway. Pages 604-609 in *Hydraulic Engineering: Proceedings of the 1990 National Conference of the Hydraulic Division of the American Society of Civil Engineers*, San Diego, California, July 30-August 3, 1990.
- Bhowmik, N. G., T. W. Soong, and W. C. Bogner. 1989. Impacts of barge traffic on waves and suspended sediments: Ohio River at river mile 581. Report by the Illinois State Water Survey, Champaign, Illinois, for the U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, Wisconsin, in fulfillment of Project Number FWS 14-16-0003-88-973, March 1989. EMTC 89-05 (October 1989). 99 pp. (NTIS # PB90 133513/AS)
- Bhowmik, N. G., T. W. Soong, W. Reichelt, and W. C. Bogner. 1990. Waves generated by recreational traffic on the Upper Mississippi River. Pages 855-860 in *Hydraulic Engineering: Proceedings of the 1990 National Conference of the Hydraulic Division of the American Society of Civil Engineers*, San Diego, California, July 30-August 3, 1990.
- Bhowmik, N. G., and T. W. Soong. 1992a. Waves generated by recreational traffic: Part I, Controlled movement. Report by the Illinois State Water Survey, Champaign, Illinois, for the U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, Wisconsin, December 1992. EMTC 92-S013. 34 pp. (NTIS #PB94-112588)
- Bhowmik, N. G., and T. W. Soong. 1992b. Waves generated by recreational traffic: Part II, Uncontrolled movement. Report by the Illinois State Water Survey, Champaign, Illinois, for the U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, Wisconsin, December 1992. EMTC 92-S016. 24 pp. (NTIS #PB94-110531)
- Bhowmik, N. G., T. W. Soong, W. F. Reichelt, and N. M. L. Seddik. 1991. Waves generated by recreational traffic on the Upper Mississippi River System. Illinois Water Survey Research Report 117. 68 pp.
- Bilby, R. 1977. Effects of a spate on the macrophyte vegetation of a stream pool. *Hydrobiologia* 56:109-112.
- Birch, S., M. G. Kelly, and B. A. Whitton. 1988. Macrophytes of the River Wear: 1966, 1976, 1986. *Transactions of the Botanical Society of Edinburgh* 45:230-242.
- Blaauw, F. C. M., F. M. C. van der Knaap, M. T. de Groot, and K. W. Pilarczyk. 1984. Design of bank protection of inland navigation fairways. Delft Hydraulics Laboratory (Netherlands). Publication 320.
- Bourne, W. S. 1932. Ecological and physiological studies on aquatic angiosperms. *Contributions from Boyce Thompson Institute* 4:425-496.
- Bowes, G., and M. E. Salvucci. 1989. Plasticity in the photosynthetic carbon metabolism of submersed aquatic macrophytes. *Aquatic Botany* 34:233-266.
- Brewer, C. A., and M. Parker. 1990. Adaptations of macrophytes to life in moving water: Upslope limits and mechanical properties of stems. *Hydrobiologia* 194:133-142.

- Brooker, M. P., D. L. Morris, and C. J. Wilson. 1978. Plant-flow relationships in the River Wye catchment. Pages 63-70 in *Proceedings of the European Weed Research Society, 5th Symposium on Aquatic Weeds*, Amsterdam, 1978.
- Brookes, A. 1988. *Channelized rivers: Perspectives for environmental management*. John Wiley and Sons, New York. 326 pp.
- Butcher, R. W. 1933. Studies on the ecology of rivers - I. On the distribution of macrophytic vegetation in the rivers of Britain. *Journal of Ecology* 21:58-91.
- Carper, G. L., and R. W. Bachmann. 1984. Wind resuspension of sediments in a prairie lake. *Canadian Journal of Fisheries and Aquatic Sciences* 41:1763-1767.
- Carstens, T. 1968. Wave forces on boundaries and submerged bodies. *Sarsia* 34:37-60.
- Carter, V., J. E. Paschal, and N. Bartow. 1985. Distribution and abundance of submersed aquatic vegetation in the Tidal Potomac River and Estuary, Maryland and Virginia, May 1978 to November 1981. U.S. Geology Survey Water-Supply Paper 2234-A.
- Carter, V., N. B. Rybicki, and R. Hammerschlag. 1991. Effects of submersed macrophytes on dissolved oxygen, pH and temperature under different conditions of wind, tide and bed structure. *Journal of Freshwater Ecology* 6(2):121-133.
- Chambers, P. A. 1987. Nearshore occurrence of submerged macrophytes in relation to wave action. *Canadian Journal of Fisheries and Aquatic Sciences* 44(9):1666-1669.
- Chambers, P. A., E. E. Prepas, H. R. Hamilton, and M. L. Bothwell. 1991. Current velocity and its effect on aquatic macrophytes in flowing waters. *Ecological Applications* 1(3):249-257.
- Chen, H. H., and D. B. Simons. 1986. Hydrology, hydraulics and geomorphology of the Upper Mississippi River System. Pages 5-19 in *Ecological Perspectives of the Upper Mississippi River*. Dr. W. Junk Publishers.
- Clafin, T. O., R. G. Rada, M. M. Smart, D. N. Nielsen, J. K. Scheidt, and B. A. Biltgen. 1981. The effects of commercial and recreational navigation on selected physical and chemical variables in Navigation Pool No. 9 Upper Mississippi River. Report for Environmental Work Team, Upper Mississippi River Basin Commission Master Plan, Minneapolis, Minnesota. 108 pp.
- Clark, W. R., and R. T. Clay. 1985. Standing crop of *Sagittaria* in the Upper Mississippi River. *Canadian Journal of Botany* 63:1453-1457.
- Collins, C. D., R. D. Sheldon, and C. W. Boylen. 1987. Littoral zone macrophyte community structure distribution and association of species along physical gradients in Lake George, New York, USA. *Aquatic Botany* 29:177-194.
- Cook, C. D. D. 1987. Dispersion in aquatic and amphibious vascular plant species. Pages 179-190 in R. M. M. Crawford, editor. *Plant life in aquatic and amphibious habitats*. Blackwell Scientific Publications, Oxford. Special Publication of the British Ecological Society No. 5.
- Coops, H., R. Boeters, and H. Smit. 1991. Direct and indirect effects of wave attacks on helophytes. *Aquatic Botany* 41:333-352.

- Crowder, A., and D. S. Painter. 1991. Submerged macrophytes in Lake Ontario: Current knowledge, importance, threats to stability, and needed studies. *Canadian Journal of Fisheries and Aquatic Sciences* 48(8):1539-1545.
- Dawson, F. H. 1978a. The seasonal effects of aquatic plant growth on the flow of water in a stream. Pages 71-78 in the *Proceedings of the European Weed Research Society, 5th Symposium on Aquatic Weeds*, Amsterdam, 1978.
- Dawson, F. H., and F. G. Charlton. 1988. A bibliography on the hydraulic resistance or roughness of vegetated watercourses. FBA, Windermere, United Kingdom. *Freshwater Biological Association Occasional Publication* 25. 50 pp.
- Dawson, F. H., and W. N. Robinson. 1985. Submerged macrophytes and the hydraulic roughness of a lowland chalk stream. *Verhandlungen des Internationalen Vereinigung für theoretische und angewandte Limnologie* 22:1944-1948.
- Day, R. T., P. A. Keddy, J. McNeill, and T. Carleton. 1988. Fertility and disturbance gradients: A summary model for riverine marsh vegetation. *Ecology* 69:1044-1054.
- Denny, M. W. 1988. *Biology and the mechanics of the wave-swept environment*. Princeton University Press, Princeton, New Jersey. 329 pp.
- Duarte, C. M., and J. Kalff. 1986. Littoral slope as a predictor of the maximum biomass of submerged macrophyte communities. *Limnology and Oceanography* 31:1072-1081.
- Eckblad, J. W. 1981. Baseline studies and impacts of navigation on the benthos and drift (Work Task 6), on the quantity of flow to side channels (Work Task 14) and on the suspended matter entering side channels (Work Task 16) of Pool 9 of the Upper Mississippi River. Prepared for the Environmental Work Team of the Upper Mississippi River Basin Commission.
- Edwards, D. 1969. Some effects of siltation upon aquatic macrophyte vegetation in rivers. *Hydrobiologia* 34:29-37.
- Fonseca, M. S., and J. S. Fisher. 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Marine Ecology Progress Series* 29:15-22.
- Fonseca, M. S., J. S. Fisher, J. C. Zieman, and G. W. Thayer. 1982. Influence of the seagrass, *Zostera marina* L., on current flow. *Estuarine, Coastal and Shelf Science* 15:351-364.
- Fonseca, M. S., and W. J. Kenworthy. 1987. Effects of current on photosynthesis and distribution of seagrasses. *Aquatic Botany* 27:59-78.
- Fonseca, M. S., J. C. Zieman, G. W. Thayer, and J. S. Fisher. 1983. The role of current velocity in structuring eelgrass (*Zostera marina*) meadows. *Estuarine, Coastal and Shelf Science* 17:367-380.
- Foot, A. L., and J. A. Kadlec. 1988. Effects of wave energy on plant establishment in shallow lacustrine wetlands. *Journal of Freshwater Ecology* 4(4):523-532.

- Fremling, C. R.. 1973. Final Report: Environmental Impact Assessment Study, Pool 5 of the northern section of the Upper Mississippi River. North Star Research Institute, Minneapolis, Minnesota.
- Gambi, M. C., A. R. M. Nowell, and P. A. Jumars. 1990. Flume observations on flow dynamics in *Zostera marina* (eelgrass) beds. *Marine Ecology Progress Series* 61:159-169.
- Grelsson, G., and C. Nilsson. 1991. Vegetation and seed-bank relationships on a lakeshore. *Freshwater Biology* 26(2):199-207.
- Håkanson, L. 1977. The influence of wind, fetch and water depth on the distribution of sediments in Lake Vänern, Sweden. *Canadian Journal of Earth Sciences* 14:397-412.
- Ham, S. F., J. F. Wright, and A. D. Berrie. 1981. Growth and recession of aquatic macrophytes on an unshaded section of the River Lambourn, England, from 1971 to 1976. *Freshwater Biology* 11:381-390.
- Ham, S. F., D. A. Cooling, P. D. Hiley, P. R. McLeish, H. R. A. Scorgie, and A. D. Berrie. 1982. Growth and recession of aquatic macrophytes in a shaded section of the River Lambourn, England, from 1971 to 1980. *Freshwater Biology* 12:1-15.
- Hamill, L. 1983. Some observations on the time of travel of waves in the River Skerne, England, and the effect of aquatic vegetation. *Journal of Hydrology* 66:291-304.
- Haslam, S. M. 1971. Physical factors and some river weeds. Pages 29-39 in *Proceedings of the European Weed Research Council, 3rd International Symposium on Aquatic Weeds*, Oxford, 1971.
- Haslam, S. M. 1978. *River plants*. Cambridge University Press, Cambridge.
- Haslam, S. M. 1987. *River plants of Western Europe: The macrophytic vegetation of watercourses of the European Economic Community*. Cambridge University Press, New York.
- Heslop-Harrison, Y. 1955. Biological flora of the British Isles, *Nuphar*. *Journal of Ecology* 43:342-364.
- Hilton, J., and G. L. Phillips. 1982. The effects of boat activity on turbidity in a shallow Broadland river. *Journal of Applied Ecology* 19:143-150.
- Hochstein, A. B., and C. E. Adams. 1989. Influence of vessel movements on stability of restricted channels. *Journal of Waterway, Port, Coastal and Ocean Engineering* 115(4):444-464.
- Hough, R. A., and M. D. Fornwell. 1988. Interactions of carbon and light availability as controlling factors in aquatic macrophyte distribution. *Limnology and Oceanography* 33:1202-1208.
- Hutchinson, G. E. 1975. *A treatise on limnology*. Volume III. Limnological botany. John Wiley and Sons, New York. 660 pp.
- Hynes, H. B. 1970. *The ecology of running waters*. University of Toronto Press. 555 pp.
- Jenkins, L. T., and M. C. F. Proctor. 1985. Water velocity, growth-form and diffusion resistances to photosynthetic CO₂ uptake in aquatic bryophytes. *Plant, Cell and Environment* 8:317-323.

- Johnstone, I. M., B. T. Coffey, and C. Howard-Williams. 1985. The role of recreational boat traffic in interlake dispersal of macrophytes: A New Zealand case study. *Journal of Environmental Management* 20:263-279.
- Jupp, B. P., and D. H. N. Spence. 1977. Limitations of macrophytes in a eutrophic Lake, Loch Leven. II. Wave action, sediments and waterfowl grazing. *Journal of Ecology* 65:431-446.
- Karaki, S., and J. Van Hoften. 1974. Resuspension of bed material and wave effects on the Illinois and Upper Mississippi Rivers caused by boat traffic. Colorado State University, Fort Collins, Colorado. CER 74-75SKJV9. 30 pp.
- Kearney, A. T., Inc. 1980. Analysis of environmental aspects of waterways navigation. Element M of the National Waterways Study. U.S. Army Corps of Engineers, Virginia. Review draft.
- Keddy, P. A. 1982. Quantifying within-lake gradients of wave energy: Interrelationships of wave energy, substrate particle size and shoreline plants in Axe Lake, Ontario. *Aquatic Botany* 14:41-58.
- Keddy, P. A. 1983. Shoreline zonation in Axe Lake, Ontario: Effects of exposure on zonation patterns. *Ecology* 64:331-344.
- Keddy, P. A. 1984. Plant zonation on lakeshores in Nova Scotia: A test of the resource specialization hypothesis. *Journal of Ecology* 72:797-808.
- Keddy, P. A. 1995. Wave disturbance on lakeshores and the within-lake distribution of Ontario's Atlantic coastal plain flora. *Canadian Journal of Botany* 63:656-660.
- Kobayashi, N., A. W. Raichle, and T. Asano. 1993. Wave attenuation by vegetation. *Journal of Waterway, Port, Coastal and Ocean Engineering* 119(1):30-48.
- Koehl, M. A. R. 1982. The interaction of moving water and sessile organisms. *Scientific American* 247:110-120.
- Koehl, M. A. R. 1984. How do benthic organisms withstand moving water? *American Zoologist* 24:57-70.
- Kristensen, P., M. Sondergaard, and E. Jeppesen. 1992. Resuspension in a shallow freshwater lake. *Hydrobiologia* 228:101-109.
- Ladle, M., and H. Casey. 1971. Growth and nutrient relationships of *Ranunculus penicillatus* var. *calcareus* in a small chalk stream. Pages 53-63 in the Proceedings of the European Weed Research Council, 3rd Symposium on Aquatic Weeds, Oxford, 1971.
- Leake, D. E., and T. M. Keevin. 1990. The development of a plan of study to evaluate the physical and biological effects of increased navigation traffic on the Mississippi River. Pages 849-854 in H. H. Chang and J. C. Hill, editors. *Hydraulic Engineering, Proceedings of the 1990 National Conference of the Hydraulics Division of the American Society of Civil Engineers*, San Diego, California, July 30-August 3, 1990.
- Lee, P. F., and J. M. Stewart. 1981. Ecological relationships of wild rice, *Zizania aquatica*. *Canadian Journal of Botany* 59:2140-2151.

- Liddle, M. J., and H. R. A. Scorgie. 1980. The effects of recreation on freshwater plants and animals: A review. *Biological Conservation* 17:183-206.
- Losee, R. F., and R. G. Wetzel. 1993. Littoral flow rates within and around submersed macrophyte communities. *Freshwater Biology* 29:7-17.
- Lubinski, K. S., N. G. Bhowmik, R. L. Evans, J. R. Adams, and M. Demissie. 1980. Identification and prioritization of study needs related to the physical, chemical and biological impacts of navigation on the Upper Mississippi River System. Illinois State Water Survey, Champaign, Illinois. Contract Report 259.
- Lubinski, K. S., H. H. Seagle, N. G. Bhowmik, J. R. Adams, M. A. Sexton, J. Buhnerkempe, R. L. Allgire, D. K. Davie, and W. Fitzpatrick. 1981. Information summary of the physical, chemical and biological effects of navigation. Report by the Illinois State Water Survey, Champaign, Illinois, for the Upper Mississippi River Basin Commission. Contract Report 261. 131 pp.
- Luttenton, M. L., J. B. Vansteenburg, and R. G. Rada. 1986. Phycoperiphyton in selected reaches of the Upper Mississippi River: Community composition, architecture and productivity. *Hydrobiologia* 136:31-46.
- Madsen, T. V., and E. Warncke. 1983. Velocities of currents around and within submerged aquatic vegetation. *Archiv fuer Hydrobiologie* 97(3):389-394.
- Madsen, T. V., H. O. Enevoldsen, and T. B. Jorgensen. 1993. Effects of water velocity on photosynthesis and dark respiration in submerged stream macrophytes. *Plant, Cell and Environment* 16:317-322.
- Marshall, E. J. P., and D. F. Westlake. 1989. Water velocities around water plants in chalk streams. *Folia Geobotanica et Phytotaxonomica, Praha*, 25:279-289.
- Martin, A. C., H. S. Zim, and A. L. Nelson. 1951. American wildlife and plants. A guide to wildlife food habit. McGraw-Hill, New York. 500 pp.
- Maynard, S. T., and T. S. Siemsen. 1991. Flow field near an inland navigation tow. Pages 610-615 in R. M. Stone, editor. *Hydraulic Engineering, Proceedings of the 1991 National Conference, American Society of Civil Engineers, Nashville, Tennessee, July 29-August 2, 1991*.
- Mazumder, B. S., N. G. Bhowmik, and T. W. Soong. 1991. Turbulence and Reynold's stress distribution in a natural river. Pages 906-911 in R. M. Stone, editor. *Hydraulic Engineering, Proceedings of the 1991 National Conference, American Society of Civil Engineers, Nashville, Tennessee, July 29-August 2, 1991*.
- Melack, J. M. 1984. Amazon floodplain lakes: Shape, fetch and stratification. *Verhandlungen de Internationalen Vereinigung fur theoretische und angewandte Limnologie*. 22:1278-1282.
- Miller, A. C., B. S. Payne, and D. V. Ragland. 1990. Studies on the physical effects of commercial navigation traffic in the Upper Mississippi River. Pages 861-866 in *Hydraulic Engineering: Proceedings of the 1990 National Conference of the Hydraulics Division of the American Society of Civil Engineers, San Diego, California, July 30-August 3, 1990*.

- Murphy, K. J., and J. W. Eaton. 1983. Effects of pleasure-boat traffic on macrophyte growth in canals. *Journal of Applied Ecology* 20:713-729.
- Nilsson, C. 1987. Distribution of stream-edge vegetation along a gradient of current velocity. *Journal of Ecology* 75:513-522.
- Nilsson, C., and G. Grelsson. 1990. The effects of litter displacement on riverbank vegetation. *Canadian Journal of Botany* 68:73-741.
- Olson, K. N., and M. P. Meyer. 1976. Vegetation, land and water surface changes in the upper navigable portion of the Mississippi River Basin over the period 1939-1973. U.S. Army Corps of Engineers, St. Paul District. Research Report 76-4.
- Ondok, J. P. 1970. The horizontal structure of reed stands (*Phragmites communis*) and its relation to productivity. *Preslia* 42:256-261.
- Ostendorp, W. 1989. 'Die-back' of reeds in Europe - A critical review of the literature. *Aquatic Botany* 35:5-26.
- Otto, N. E., and E. P. Enger. 1960. Some effects of suspended sediments on growth of submersed pondweeds. U.S. Department of Interior, Bureau of Reclamation, Division of Engineering Laboratories, Denver, Colorado. General Laboratory Report 227.
- Petryk, S., and G. Bosmajian. 1975. Analysis of flow through vegetation. *Proceedings, Hydraulics Division, American Society of Civil Engineers* 101:871-874.
- Phillips, G. L., D. Eminson, and B. Moss. 1978. A mechanism to account for macrophyte decline in progressively eutrophicated freshwaters. *Aquatic Botany* 4:103-126.
- Pitlo, R. H., and F. H. Dawson. 1990. Flow-resistance of aquatic weeds. Pages 75-84 in A. H. Pieterse and K. J. Murphy, editors. *Aquatic weeds. The ecology and management of nuisance aquatic vegetation*. Oxford University Press.
- Pitlo, R. H. 1982. Flow resistance of aquatic vegetation. Pages 225-234 in the *Proceedings of the European Weed Research Society, 6th Symposium on Aquatic Weeds*, Novi Sad, 1982.
- Poe, T. P., and T. A. Edsall. 1982. Effects of vessel-induced waves on the composition and amount of drift in an ice environment of the St. Mary's River. U.S. Fish and Wildlife Service, Great Lakes Fisheries Laboratory. AR 82-6. 45 pp.
- Rasmussen, J. L. 1983. A summary of known navigation effects and a priority list of data gaps for the biological effects of navigation on the Upper Mississippi River. Contract No. NCR-LO-83-C9 by the U.S. Fish and Wildlife Service, Rock Island, Illinois, prepared for the U.S. Army Engineer District, Rock Island, Illinois. 96 pp.
- Raynal, D. J., and J. W. Geis. 1978. Environmental assessment of the FY 1979 winter navigation demonstration on the St. Lawrence River. State University of New York, Syracuse. Technical Report G. 14 pp.
- Roberts, J., and J. A. Ludwig. 1991. Riparian vegetation along current-exposure gradients in floodplain wetlands of the River Murray. *Journal of Ecology* 79(1):117-127.

- Rorslett, B. 1969. On the dispersal of *Elodea canadensis* Michx. in the lowlands of southeast Norway 1961-1968. *Blyttia* 27:185-193.
- Roseboom, D. P., R. M. Twait, and T. E. Hill. 1992. Physical characteristics of sediment and habitat affecting aquatic plant distribution in the Upper Mississippi River System: FY 90. Report by the Illinois State Water Survey, Peoria, Illinois, for the U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, Wisconsin, December 1992. EMTC 92-S011. 77 pp. (NTIS #PB94-109964)
- Rybicki, N. B., and V. Carter. 1986. Effect of sediment depth and sediment type on the survival of *Vallisneria americana* Michx. grown from tubers. *Aquatic Botany* 24:233-240.
- Schloesser, D. W., and B. A. Manny. 1982. Distribution and relative abundance of submersed macrophytes in the St. Clair-Detroit Rivers ecosystems. U.S. Fish and Wildlife Service. Administration Report No. 82-7. 49 pp.
- Schloesser, D. W., and B. A. Manny. 1989. Potential effects of shipping on submersed macrophytes in the St. Clair and Detroit Rivers of the Great Lakes. *Michigan Academician* 21:110-118.
- Schneider, R. L., and R. R. Sharitz. 1988. Hydrochory and regeneration in a bald cypress-tupelo swamp forest. *Ecology* 69(4):1055-1063.
- Schoellhamer, D. H., and V. A. Levesque. 1991. Wind generated wave resuspension of sediment in Old Tampa Bay, Florida. Pages 85-90 in R. M. Stone, editor. *Hydraulic Engineering, Proceedings of the 1991 National Conference, American Society of Civil Engineers, Nashville, Tennessee, July 29-August 2, 1991.*
- Sculthorpe, C. D. 1967. The biology of aquatic vascular plants. St. Martin's Press, New York. 610 pp.
- Simon, N. S. 1989. Nitrogen cycling between sediment and the shallow-water column in the transition zone of the Potomac River and Estuary II. The role of wind-driven resuspension and absorbed ammonium. *Estuarine, Coastal and Shelf Science* 28:531-547.
- Simons, D. B., Y. H., Chen, R-M. Li, and S. S. Ellis. 1981. Assistance in evaluation of the existing rivers environment and assessment of impacts of navigation activity on the Upper Mississippi River System. SLA Associates, Fort Collins, Colorado. 34 pp. + appendix
- Simons, D. B., R. K. Simons, M. Ghaboosi, and Y. H. Chang. 1988. Physical impacts of navigation on the Upper Mississippi River System. Report to U.S. Army Corps of Engineers St. Louis District. 9 chapters + appendix.
- Sirjola, E. 1969. Aquatic vegetation of the River Teuronjoki, South Finland and its relation to water velocity. *Annales Botanicae Fennici* 6:68-75.
- Smart, M. M., R. G. Rada, D. N. Nielsen, and T. O. Clafflin. 1985. The effect of commercial and recreational traffic on the resuspension of sediment in Navigation Pool 9 of the Upper Mississippi River. *Hydrobiologia* 126:263-274.
- Sorenson, R. M. 1973. Water waves produced by ships. *Journal of Waterways, Harbors and Coastal Engineering Division, American Society of Civil Engineers* 99:245-256.

- Sparks, R. E. 1975. Possible biological impacts of wave wash and resuspension of sediments caused by boat traffic in the Illinois River. Report for Corps of Engineers, St. Louis District, Missouri. 23 pp.
- Sparks, R. E. 1984. Role of contaminants in the decline of the Illinois River: Implications for the Upper Mississippi River. Pages 25-66 *in* Contaminants in the Upper Mississippi River. Butterworth, Boston.
- Sparks, R. E. , R. C. Thomas, and D. J. Schaeffer. 1980. The effects of barge traffic on suspended sediments and turbidity in the Illinois River. Report for U.S. Fish and Wildlife Service, Rock Island Field Office, Illinois. 68 pp.
- Spence, D. H. N. 1982. The zonation of plants in freshwater lakes. *Advances in Ecological Research* 12:37-125.
- Stark, H., and M. Dienst. 1989. Dynamics of lakeside reed belts at Lake Constance (Untersee) from 1984-1987. *Aquatic Botany* 35:63-70.
- Stefan, H. F., and K. J. Anderson. 1980. Wind-driven flow in Mississippi River impoundment. *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers* 106:1503-1520.
- Stefan, H. F., and M. F. Riley. 1985. Mixing of a stratified river by barge tows. *Water Resources Research* 21:1085-1094.
- Sukopp, H. 1971. Effects of man, especially recreational activities, on littoral macrophytes. *Hydrobiologia (Bucaresti)* 12:331-340.
- U.S. Army Corps of Engineers. 1989. Draft Plan of Study, navigation effects of the second lock, Melvin Price Locks and Dam. 278 pp.
- U.S. Army Corps of Engineers. 1993. Mississippi River and Illinois Waterways Navigation Study Initial Project Management Plan. U.S. Army Engineer District, Rock Island, Illinois.
- U.S. Fish and Wildlife Service. 1987. Supplemental draft, Fish and Wildlife Coordination Act report for Lock and Dam 26 (replacement) second lock. Draft Environmental Impact Statement.
- U.S. Fish and Wildlife Service. 1992. Operating Plan for the Upper Mississippi River System Long Term Resource Monitoring Program. Environmental Management Technical Center, Onalaska, Wisconsin, Revised September 1993. EMTC 91-P002. 179 pp. (NTIS #PB94-160199)
- Vermaat, J. E., and R. J. De Bruyne. 1993. Factors limiting the distribution of submerged water plants in the lowland River Vecht (The Netherlands). *Freshwater Biology* 30:147-157.
- Vogel, S. 1984. Drag and flexibility in sessile organisms. *American Zoologist* 24:37-44.
- Vohs, P. A., I. J. Moore, and J. S. Ramsey. 1993. A critical review of the effects of turbidity on aquatic organisms in large rivers. Report by Iowa State University, Ames, Iowa, for the U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, Wisconsin, March 1993. EMTC 93-S002. 139 pp. (NTIS # PB94-110228)

- Ward, L. G., W. M. Kemp, and W. R. Boynton. 1984. The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. *Marine Geology* 59:85-103.
- Weisner, S. E. 1987. The relation between wave exposure and distribution of emergent vegetation in a eutrophic lake. *Freshwater Biology* 18:537-544.
- Weisner, S. E. B. 1991. Within-lake patterns in depth penetration of emergent vegetation. *Freshwater Biology* 26:133-142.
- Weller, M. W. 1981. *Freshwater marshes*. University of Minnesota Press, Minneapolis. 146 pp.
- Westlake, D. F. 1967. Some effects of low velocity currents on the metabolism of aquatic macrophytes. *Journal of Experimental Botany* 18:187-205.
- Westlake, D. F. 1975. Macrophytes. Pages 106-128 in B. A. Whitton, editor. *River ecology*. University of California Press.
- Wetzel, R. G. 1983. *Limnology*. Second Edition. Saunders College Publishing, Philadelphia. 762 pp.
- Wetzel, R. G. 1988. Water as an environment for plant life. Pages 1-30 in *Vegetation of inland waters*. Kluwer Academic Publishers, Boston.
- Wilson, L. R. 1935. Lake development and plant succession in Vilas County, Wisconsin. Part I. The medium hard water lakes. *Ecological Monographs* 5:207-247.
- Wisheu, I. C., and P. A. Keddy. 1991. Seed banks of a rare wetland plant community: Distribution patterns and effects of human-induced disturbance. *Journal of Vegetation Science* 2:181-188.

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13. ABSTRACT (Maximum 200 words) This report embodies a review describing the potential impacts on aquatic vegetation from waves generated by commercial and recreational vessel traffic, and contrasts these impacts with effects of natural forces. The review was undertaken as part of a Corps of Engineers study on navigation impacts on the Upper Mississippi River. Interactions between waves and aquatic vegetation are summarized in the report. Waves act directly by uprooting or fragmenting plants. Wave action can resuspend and transport sediments, resulting in altered sediment texture and sediment resuspension. Changes in sediment texture potentially affect plant nutrition. Resuspended sediments can limit plant photosynthesis, due to reduced availability of underwater light. Wave energy can also be important in the burial or dispersal of plant propagules. Changes in wave energy regimes may affect plant species composition and abundance, potentially leading to changes in other components of aquatic systems. While affected by wave energy, aquatic plants also dissipate this energy which, in turn, may result in localized areas of decreased sediment resuspension and increased sediment accretion. Thus, effects of wave energy on aquatic vegetation can be expected to vary with differences in plant abundance as well as position with respect to wave regimes.				
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The Long Term Resource Monitoring Program (LTRMP) for the Upper Mississippi River System was authorized under the Water Resources Development Act of 1986 as an element of the Environmental Management Program. The mission of the LTRMP is to provide river managers with information to maintain the Upper Mississippi River System as a viable large river ecosystem given its multiple-use character. The LTRMP is a cooperative effort by the National Biological Survey, the U.S. Army Corps of Engineers, and the states of Illinois, Iowa, Minnesota, Missouri, and Wisconsin.



